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THE PROBLEM OF PROLONGED, AUTONOMOUS HUMAN EXISTENCE IN A SPACE SUIT

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ABSTRACT

The authors consider the feasibility of maintaining the thermal balance of a cosmonaut in a space suit utilizing only physiological perspiration. Two series of tests were conducted in a thermal pressure chamber to determine the degree of intensity of physiological heat control and the performance capacity and the general condition of an organism. On the basis of the experiments it is asserted that for a period of 3 to 4 hours a man in a space suit is able to dissipate by the evaporation of perspiration 200-220 kcal/hr of heat produced either internally or externally. When the total thermal load is decreased, the duration a man can withstand such condition is greatly increased.

Maintaining the thermal balance of the organism of a man wearing a space suit in open cosmic space or in a cabin with the hermetic seal broken entails certain technical problems, the successful solution of which necessitates the determination of the physiological capabilities of the organism of a man exposed to conditions so unusual for him. /1*

At the present time, research and design work has been done which has made it possible to create varying heat control systems for space suits. The main problem in a heat control system for a space suit is the removal of endogenic heat, the amount of which fluctuates within wide limits (from 90 to 500 kcal/hr) depending on the activities which the cosmonaut performs. Thermal exchange between the space suit and the surrounding space by radiation can be kept to a minimum by using screening-vacuum thermal insulation.

Most of the systems which have been developed are based on the use of the latent heat derived from the evaporation of water. The intensity of this process and, consequently, the cold productivity of the system under the conditions obtained in space can easily be regulated by the use of the vacuum of outer space for this purpose. Heat removal from the space enclosed by the space suit is accomplished either by direct contact between the evaporating water and the outer jacket of the space suit, or by use of evaporative or sublimative thermal exchangers with liquid or air circuits. During the use of air circuits, and in some other cases, heat exchange by perspiration has a considerable role in the heat exchange mechanism of a man in a space suit. In some cases (with /2

*Numbers given in the margin indicate the pagination in the original foreign text.

inadequate cooling of the air used for ventilation or external thermal evaporation may prove to be the only way to release the heat produced by the organism.

In this report consideration is given to the feasibility of maintaining the thermal balance of a cosmonaut in a space suit utilizing only physiological perspiration. Direct use of evaporation of the liquid deposited on the skin and in the lungs for removing endogenic heat and compensation for the external heat load proved to be most advantageous from the point of view of expenditure of materials and energy. The technological solution of this task could be the simplest possible, almost precluding the possibility of failure or breakdown. The shortcomings of such a heat removal system are obvious. By utilizing this system we knowingly fail to create a comfortable heat regime and to maintain a normal thermal balance.

Two series of tests were conducted in a thermal pressure chamber for the purpose of determining the degree of intensity of physiological heat control and performance capacity and the general condition of an organism.

In the first series of tests, conducted at a high temperature (more than +40 C), a study was made of an organism's capability to compensate for the effects of an external thermal load for a relatively short period of time (from 2 to 10 hours) under conditions of both relative quiet and physical activity. The value of the external thermal load was introduced by creating appropriate temperatures inside the thermal pressure chamber.

The subjects were dressed in space suits ventilated with dry air in a quantity which provided almost complete evaporation of the perspiration released. To avoid dehydration of the organism in tests lasting more than 3 hours, the subjects were given an unlimited (but strictly measured) amount of liquid. An absolute pressure of 354--267 mmHg was maintained in the space suit. The state of thermal exchange of the subjects was evaluated from temperature indicators and indicators of the primary physiological functions. During the tests, recordings were made of the rectal temperature, the skin temperature in 5 places, the temperature of the space within the space suit, the heat production as determined from a study of gas exchange in the lungs, moisture loss, effectiveness of evaporation of perspiration, and heart and respiration rates.

A total of 25 tests were made with the participation of 7 test subjects. The basic results are shown in Table 1.

From the information presented in the table, it follows that during a 2-hour exposure of the subjects in the thermal chamber, with an external thermal load equal to 133 kcal/hr, the initial signs of overheating were noted. The temperature of the body rose by 0.3° and the heart rate increased somewhat. The value of the overall thermal load in these experiments was 219 kcal/hr and the loss of moisture equal to 357 g/hr. All perspiration was completely evaporated. /3

With a decrease in the external thermal load and with the total load kept at approximately the same level (by performance of measured physical work) no signs of overheating were observed even with longer exposure. In this case the loss of moisture by the subjects was somewhat greater and came to 398 g/hr.

Table 1

Several Indicators of Heat Exchange in Subjects Tested in Experiments Conducted at a High Temperature in a Thermal Pressure Chamber (mean data)

Indicators	Groups of tests		
	First	Second	Third
Duration (hr)	10	3	2
Total thermal load on subject (kcal/hr)	119	204	219
Production of heat (kcal/hr)	73	141	86
External thermal load (kcal/hr)	46	63	133
Accumulation of heat in organism (kcal/hr)	0	0	9
Moisture loss in subject (g/hr)	210	398	357
Evaporation of perspiration (in % of moisture loss)	100	89	100
Change in pulse rate during test (in % of initial value)	-2	+3	+3

With lower quantities of external thermal load (on the order of 46 kcal/hr) the condition of the subjects was somewhat better, the losses of moisture were reduced to 210 g/hr, and the subjects rated the temperature as "warm." The subjects remained in the thermal pressure chamber 10 hours each. During this period their overall condition did not change with the exception of general fatigue occurring at the end of the experiment.

The results of the tests agree with information in the available literature that muscular work is a more active stimulant of perspiration than external heat acting on the skin exteroceptors. Apparently increasing the external thermal load will be tolerated by cosmonauts with more difficulty than an equal increase in heat production of the organism due to an increase in physical activity.

In this way the experiments which were conducted make it possible to state that a man in a space suit is able, for a certain period of time (on the order of 3--4 hours), to dissipate by the evaporation of perspiration 200--220 kcal/hr of heat produced either internally or externally. When the total thermal load is decreased, the time that a man can withstand such /4 conditions is greatly increased.

For the purpose of determining the capability of an organism to maintain a thermal balance for an extended period of time through thermal exchange by evaporation, a series of 7-day experiments were conducted during the spring-summer period of the year in a thermal pressure chamber in which conditions were created to simulate, as far as heat was concerned, flight in the cabin of an unsealed spaceship.

The subjects (three healthy men ranging in age from 21 to 38 years) were dressed in space suits in which an absolute pressure of 300 mmHg was maintained. The residual pressure in the test chamber was 5--6 mmHg and the pressure levels in the test chamber and the space suit did not vary during the entire experiment. To preclude thermal exchange through the outer covering of the space suit, the temperature of the chamber walls and the internal air were kept at a level corresponding to the temperature of the gas mixture inside the space suit.

The subject was seated in a special chair wearing a carefully adjusted space suit. By means of an electric drive system, the angle of incline of various parts of the chair could be changed within a wide range and it could even convert into a horizontal surface. The necessary life-support conditions were provided for the subjects by special laboratory systems which did not require a change in the pressure in the cahamber and the space suit. Food was delivered to the space suit in liquid form. Consumption of water was unlimited. Pure oxygen was fed to the helmet for breathing. The muscular activity of the subjects was limited to controlling the life-support systems and executing functional tests for purposes of studying the condition of the cardiovascular system.

In the experiments use was made of two modes for ventilating the space suit. In one, the temperature of the air being delivered to the space suit was similar to the temperature on the surface of the body and all endogenic heat was removed by the evaporation of perspiration. In the other mode, 25-40% of the heat was removed from the space suit for purposes of heating the air used for ventilation.

While studying the body heat of the subjects measurements were made of the energy consumed, loss of moisture other than through the kidneys, the temperature of the body (under the tongue) of the skin (in 7 places), and of the air leaving the space suit, and also the temperature and humidity of the air inside the space suit. A calculation of the heat exchange in the subjects was made based on the indicators named above.

In addition to a study of the heat in the bodies of the subjects, a study was made of the dynamics of several functional indicators of the cardiovascular system, respiration, metabolic processes, and performance capacity.

The maximum duration of one experiment was 7 days 17 hours. One experiment was terminated at the end of 4 days because of marked deterioration /5 in the condition of one of the subjects. The changes in condition took the form mainly of overheating of his body and reduction in the functioning capacity of the cardiovascular system.

As a result of the investigation which was performed, it was established that the complex of effects associated with a prolonged stay by man in a space suit under conditions of excess pressure at an "altitude" results in a serious strain on the organism, requiring constant and protracted effort on the part of compensatory mechanisms. During the first 3 days, the overall condition of all the subjects and the level of their performance ability did not reflect any significant changes. On the 4th and 5th days, changes in the functional condition of the subjects appeared which were directly related to the extent and duration of the effects of heat (Table 2).

Table 2

Heat Exchange and Water Consumption during Prolonged Stay in a Space Suit at an Altitude (mean daily values)

Indicators	Subjects			
	A	B	C	
	1st-7th days	1st-4th days	1st-5th days	6th-7th days
Heat production (kcal/day)	1907	2038	2324	2450
Heat released by evaporation (kcal/day)	1241	2118	2319	1416
Heat released to warm ventilating air (kcal/day)	451	108	95	787
Heat released through the outer layer of the space suit (kcal/day)	-215	+188	-90	-247
Loss of moisture other than through the kidneys (g/day)	2141	3653	3999	2442
Water consumption (g/day)	2767	4435	4429	2518
Change in weight of body during the test (g)	+650	+3650	+1600	

Note: The heat released through the outer layer of the space suit with a plus (+) sign indicates heat flow into the space suit and with a minus (-) sign heat flow out of the space suit.

The differences in the way in which heat was released by the subjects led, at the end of the experiments, to very great differences in their overall condition. In the case of A, whose space suit for all 7 days was ventilated with cooled air, no marked strain on the temperature control system was noted. The body temperature stayed within the limits of 36.5-37.2°C and the average temperature of the skin within the limits of 34.6-36.3°C (Fig. 1). The heart rate in a state of relative quiet did not exceed

80 beats/min. The daily loss of moisture other than through the kidneys was equal to 2140 g. The subject rated his heat condition as "warm". In a clinico-physiological examination after the experiment, no significant changes in comparison with initial data were noted. The changes noted were explained by overall fatigue and relative hypodynamia during the 7 days of the experiment.

In the experiments involving an increased thermal load wherein almost all endogenic heat was removed through evaporation of perspiration (experiment conduted with B and the first 5 days of the experiment conducted with C) the strain on the heat control system was more marked. Loss of moisture other than through the kidneys was 3650--4000 g/day.

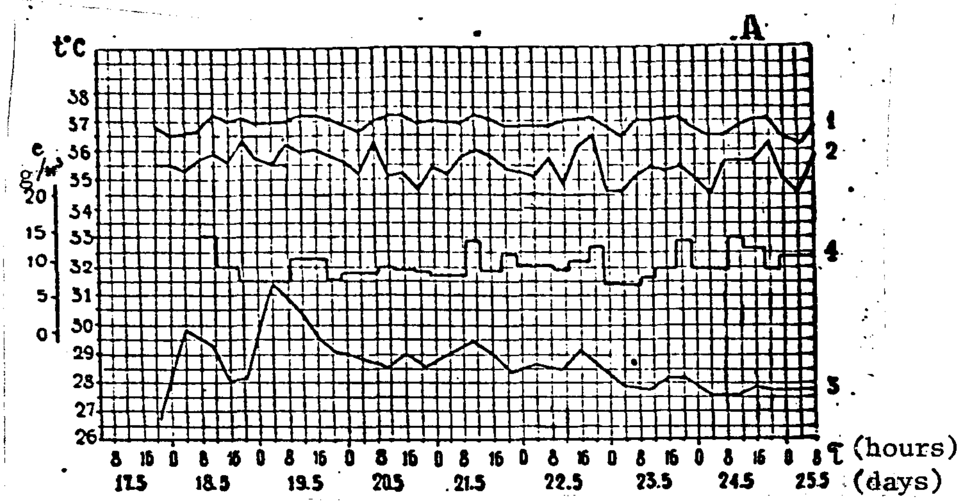

Fig. 1. Dynamics of body temperature, weighted mean average of skin temperature, moisture, and temperature of the air leaving the space suit in the experiment conduted with A:

1--body temperature (under the tongue); 2--weighted mean skin temperature; 3--air temperature on leaving the space suit; 4--moisture in air on leaving the space suit.

For the first 3 days of the test it was possible to maintain the heat balance of the organism as is reflected by the relatively stable temperature of the body and the skin (Fig 2). However, on the 4th day, in both subjects, symptons of overheating of the organism began to appear, manifested through increases in body temperature and increases in frequency of cardiac contraction began to appear. Gradually increasing, these phenomena attained their maximum values on the 5th day. The experiment with B was terminated. The temperature of the air being delivered to B's space suit was lowered to normalize his heat balance. In 6 hours B's heat balance was relatively normal again. The body temperature dropped to 37.5°C and the heart rate dropped to 64--72 beats/min. During the next 2 days of the test, the body temperature remained within /7 the limits of 37.0--37.6°C. The level of the skin temperature exceeded normal values somewhat and was equal to 35.5--36.5°C.

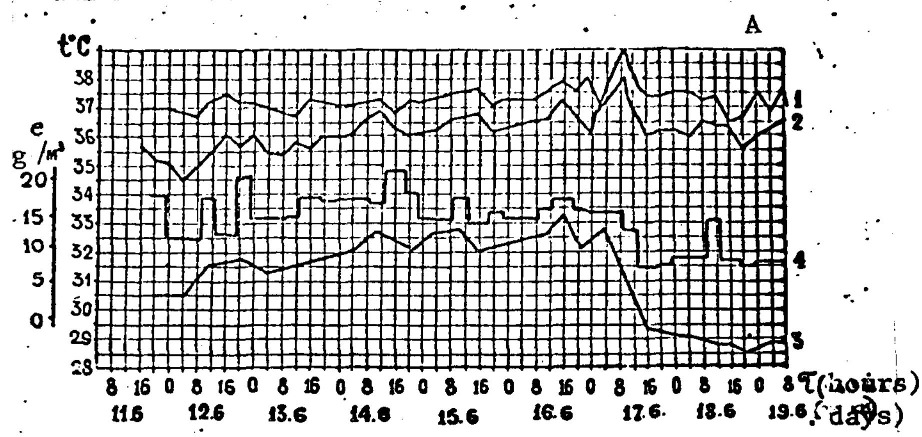

Fig. 2. Dynamics of body temperature, weighted mean skin temperature and moisture and temperature of the air leaving the space suit in the test with C.

Key is same as for Fig. 1.

The reason for such marked changes in the heat balance of B and C on the 4th day of the experiment, in all probability, was strain on the heat control mechanism which was exposed to constant stress over an extended period of time. This applies particularly to the function of perspiration. With the unlimited water consumption in C, the loss of moisture other than through the kidneys decreased somewhat and this might have caused gradual overheating.

During a clinico-physiological check after the experiment with B, marked fatigue with astheno-vegetative reactions was noted and also hypostatic edema of the lower extremities. The edema of the lower extremities which was found probably had a dual nature. On one hand, the edema may have been a result of remaining for an extended period in a fixed position with the feet down, and on the other, a consequence of an increase in the permeability of the capillaries and disruption of the electrolyte balance with increased loss of moisture other than through the kidneys.

Providing for somewhat freer movement and an opportunity to rest and sleep in a horizontal position with the feet elevated in the experiment conducted with A and also a decrease in the heat load precluded the development of edema. According to data from hydrostatic weighing (materials of A. G. Zhanova), in A the non-fatty component of the body (primarily the water component) increased by only 350 g. In C, who was given a chance, during /8 the experiment under condition of increased thermal load, to sleep and rest in a horizontal position, no edema was found. However, after the test the water component of the body was found to be 1000 g heavier. Moreover, during the last days of the test when the thermal load was decreased, a marked increase in the urine passed (1525 g/day) was observed in comparison with indicators for the preceding days (500--740 g/day). The quantity of urine in A and B in the experiment was 663 and 758 g/day, respectively.

Such a high diuresis with a relatively small water consumption and still significant losses of moisture other than through the kidneys is evidence, apparently, of the latent edema which began to develop after the decrease in the thermal load. The following diagnosis was given for C after the experiment: fatigue, vascular-vegetative instability. During the next 3 days all changes which had been observed disappeared.

Thus, during the experiments in which all the heat released by the subjects was released through evaporation of perspiration, maintaining a thermal balance was possible to 3--4 days after which symptoms of overheating of the body appeared. After 4--5 days signs of wear on the heat control system appeared, accompanied by overheating. Conditions in which 25--40% of the endogenic heat is removed to heat the air used for ventilation are completely tolerable for a protracted time although they are associated with a certain strain on the heat control system. It was also proven in principle that, life could be supported and that a cosmonaut could work in his space suit for a period of 7 days, if the seal of the cabin of the spaceship is broken in an emergency.

It should be stressed that this conclusion applies to test subjects who had not been acclimated and who remained in a state of relative quiet (mean daily expenditure of energy 1900--2400 kcal) when movement was greatly limited and water consumption unlimited.

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